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14. ABSTRACT
The purpose of this technical paper is to present the underlying logic and algorithms used in risk-based explosives safety analyses. Quantity-Distance (QD) criteria have been used as the primary means for the safe siting of facilities for more than 70 years. Current QD criteria consider only explosives quantity, Hazard Division (HD), and facility type to determine a safe separation distance. QD siting assumes that someday the accident will happen and mandates minimum stand-off distances to mitigate the hazards. During the past 30 years, safety professionals have recognized that QD could be improved by considering other factors in the safety analyses to include type of activity, number of people present, building construction, and environment to assess the overall risk of an operation. The level of risk can be quantified as a function of (1) the probability of an explosives event, (2) probability of personnel being exposed to the event, and (3) the probability of injury or fatality due to exposure. Explosives safety siting of energetic liquids and propellants can be greatly aided by the use of risk-based methodologies. The low probability of exposed personnel and the characteristic protective construction found at test locations or facilities utilizing energetic liquids typically lead to low hazard probabilities. Department of Defense Explosives Safety Board (DDESB) Technical Paper 14 details general risk-based siting criteria accepted in the U.S. Risk-based analyses can also be used for risk management purposes and comparative studies when evaluating test programs that utilize energetic liquids or propellants.

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RISK-BASED EXPLOSIVE SAFETY ANALYSIS

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ABSTRACT

The purpose of this technical paper is to present the underlying logic and algorithms used in risk-based explosives safety analyses. Quantity-Distance (QD) criteria have been used as the primary means for the safe siting of facilities for more than 70 years. Current QD criteria consider only explosives quantity, Hazard Division (HD), and facility type to determine a safe separation distance. QD siting assumes that someday the accident will happen and mandates minimum stand-off distances to mitigate the hazards. During the past 30 years, safety professionals have recognized that QD could be improved by considering other factors in the safety analyses to include type of activity, number of people present, building construction, and environment to assess the overall risk of an operation. The level of risk can be quantified as a function of (1) the probability of an explosives event, (2) probability of personnel being exposed to the event, and (3) the probability of injury or fatality due to exposure. Explosives safety siting of energetic liquids and propellants can be greatly aided by the use of risk-based methodologies. The low probability of exposed personnel and the characteristic protective construction found at test locations or facilities utilizing energetic liquids typically lead to low hazard probabilities. Department of Defense Explosives Safety Board (DDESB) Technical Paper 14 details general risk-based siting criteria accepted in the U.S. Risk-based analyses can also be used for risk management purposes and comparative studies when evaluating test programs that utilize energetic liquids or propellants.

INTRODUCTION

Explosives site planning is a process of comprehensive analysis of existing and future mission requirements needed to build, modify, expand, or otherwise alter or change the functional use of any facility where explosives or an explosives clear zone is involved[1]. Explosives safety site plans are required of all Department of Defense (DoD) facilities where explosives materials are used. The process is ultimately governed by the Department of Defense Explosives Safety Board (DDESB) using DoD Manual 6055.09-M, *DoD Ammunition and Explosives Safety Standards*2. Each service agency has a service-level approval authority (e.g. Air Force Safety Center, Naval Ordnance Safety & Security Activity (NOSSA), United States Army Technical Center for Explosive Safety (USATCES)) and additional criteria specific to their operational needs.

For more than 90 years, Quantity-Distance (QD) criteria have been used in making explosives safety judgments. QD-based siting considers the potential explosion site (PES) and exposed site (ES) facility types, the distance separating the facilities, and the amount of stored munition or energetic material. This is a deterministic methodology that assumes an explosives accident will happen someday and specifies stand-off requirements intended to keep personnel at safe distances.

For the last 30 years, it has been recognized that the QD methodology could be improved. The analysis could be expanded to include other considerations to assess the overall explosives risks of the operation. These considerations include the type of explosives activity being conducted, the number of people exposed and their exposure time, the relationship of exposed personnel to the explosives activity being conducted, PES and ES building construction, and environment. In the last 10 years, the DDESB has overseen the development of Quantitative Risk Assessment (QRA) methodologies.

The purpose of this technical paper is to present the underlying logic and algorithms used in risk-based explosives safety analyses. The risk-based approach is compared to the current QD methodology

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with an emphasis on how each handles the unique aspects of energetic liquids. Other uses of risk-based analyses are discussed, including risk management and comparative studies.

RESULTS AND DISCUSSION

OVERVIEW OF THE QUANTITY-DISTANCE APPROACH

Quantity-Distance siting seeks to provide an acceptable level of safety to facilities and personnel by controlling either the distance between facilities or the amount of munitions and explosives stored. The required distance between facilities is determined by use of the formula $D=K \times W^{1/3}$, where D is the distance in feet, W is the net equivalent weight of explosives in pounds, and K is a variable coefficient determined by the level of hazard permitted or the level of safety required (e.g. Inhabited Building Distance (IBD) K=40 or Public Transportation Route Distance (PTRD) K=24). If the required distances cannot be obtained, an alternative is to reduce the quantity of explosives. If such a reduction cannot be achieved and the mission is jeopardized, a waiver or exemption may be requested.

Strengths of the QD methodology are that it is often conservative and it is generally simple to apply, requiring only basic information. If the required distance is not difficult to achieve, compliance with the standard is straightforward. The weaknesses of this methodology are that its criteria are inflexible to site-specific operations and require obtaining waivers or exemptions for noncompliance3. Waivers or exemptions can require costly engineering analyses to account for site-specific protective construction. Another potential weakness is that the QD methodology may not capture all aspects of risk associated with a given scenario.

INTRODUCTION TO QUANTITATIVE RISK ASSESSMENTS

Quantitative Risk Assessment seeks to calculate the level of hazard for individuals and groups. This differs from the QD deterministic method of labeling each facility as either “acceptable” or “in violation”. Two scenarios are provided to illustrate the differences.

A PES facility contains 100,000 pounds TNT equivalency. The IBD for this scenario would be 1,857 feet. In the first scenario (see Figure 1) a single vacation home is located just within the IBD arc determined by QD. This vacation home sees visitors only a few days a year. QD criteria would require the removal of the hazard by either reducing the allowable storage at the PES or moving/closing the home. QD deterministic criteria conservatively assume that the accident will happen and that the exposed personnel will be hurt or killed.

A risk-based analysis would seek to quantify the hazard by collecting details of the personnel exposure, PES function, and type of building construction. The risk-based methodology asks, “Given site-specific information, is the situation safe enough?” In the case of scenario 1, the mission of the PES would not need to be jeopardized if the risk to personnel in the vacation home is acceptably low.

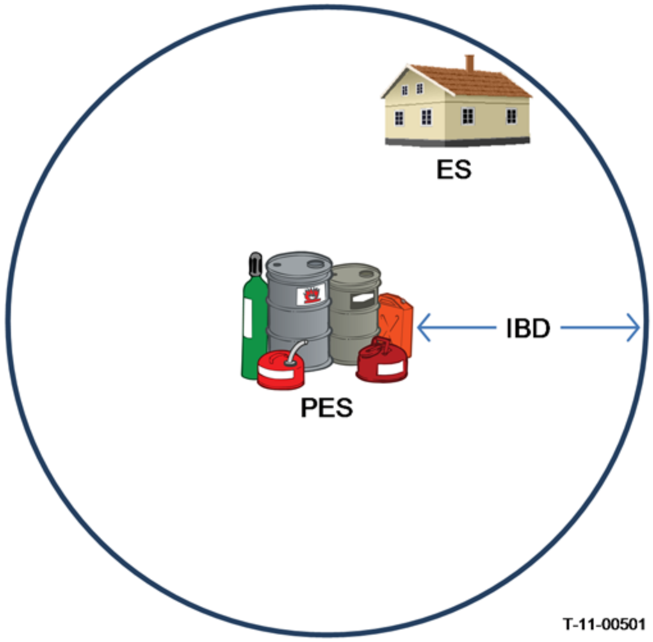

Figure 1 – Scenario 1

The second scenario (see Figure 2) consists of an identical PES facility surrounded by multiple highly-populated buildings. The buildings are located just outside of the standard IBD arc. This scenario is acceptable according to QD criteria.

A risk-based analysis of scenario 2 would likely determine that the hazard of death or injury to any single person is low due to the separation distance. However, risk-based criteria consider the risk of the entire situation. The individual risk is multiplied by number of people present. In this scenario it is likely that hundreds or thousands of people are present most days. This scenario could result in an unacceptable level of risk. This hazard could be mitigated by reducing the number of exposed personnel, reducing the PES storage, increasing separation distance, or reducing the time in which explosives and personnel are present at the same time.

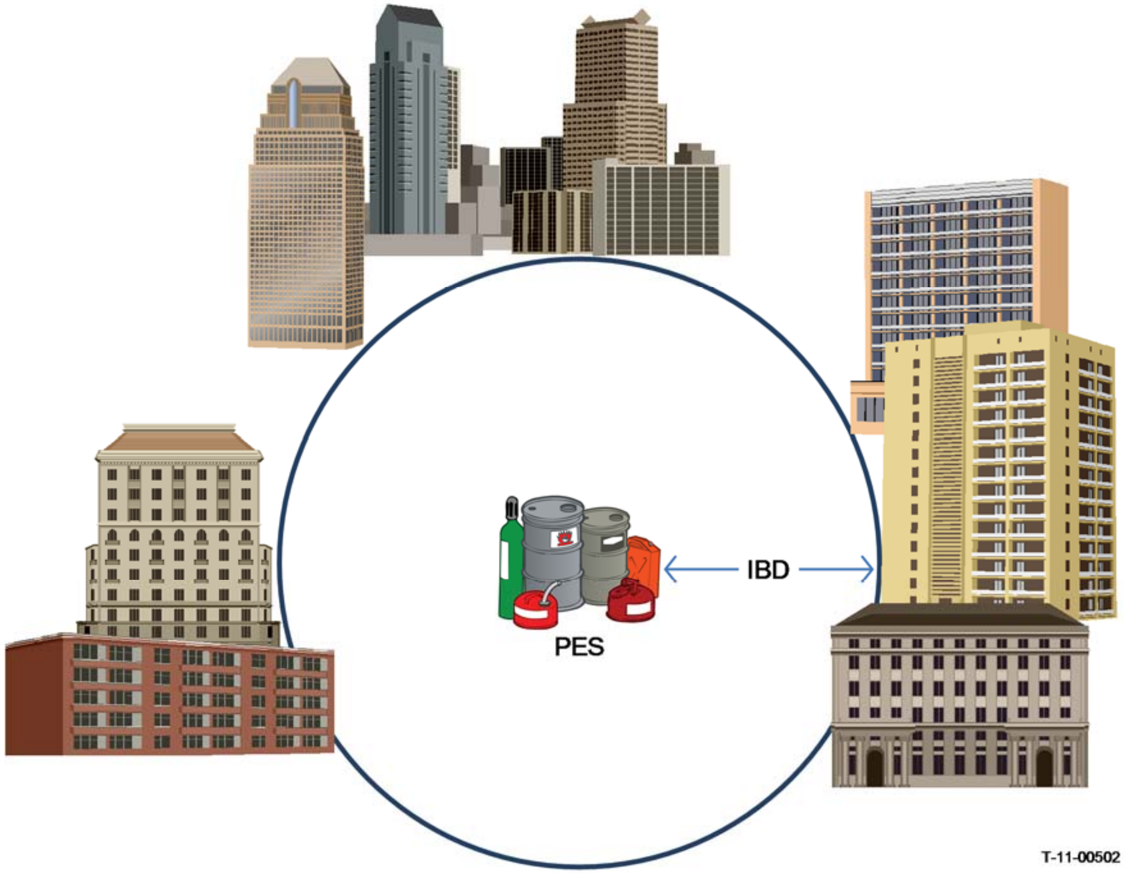

Figure 2 – Scenario 2

These scenarios demonstrate that the amount of risk in a situation depends heavily upon the personnel exposure. Scenarios with the same PES, explosives quantity, and standoff distance can still have dramatically different levels of risk. It is also demonstrated that QRA does not always result in a lower required separation distance. This type of analysis requires more information than QD analysis, but has the potential to more accurately describe the situation and quantify the hazards.

QUANTITATIVE RISK ASSESSMENT METHODOLOGY

The QRA methodology described in this paper is detailed in DDESB Technical Paper 14, *Approved Methods and Algorithms for DoD Risk-Based Explosives Siting*[4]. Risk is assessed according to the following formula:

$$E_f = E_p \times P_{f|e} \times P_e$$

Where E_f = expected fatalities per year
E_p = expected exposure of people in hours per year
$P_{f|e}$ = probability of fatality given an event
P_e = probability of event per PES facility per year

The basic method defined by this equation can be applied to many varying circumstances. The three terms used to determine the expected fatalities are discussed individually, followed by a description of the overall architecture of the process.

EXPOSURE

The E_p term describes the amount of time, in terms of hours per year, which an individual is present at the same time explosives or energetic materials are being handled or stored. The total exposure used for the calculation is the aggregation of all individual exposure. This final value may include hundreds of people or more if many ES facilities are exposed to the PES.

This term can account for complex work schedules, multiple working groups, and in-transit operations. The exposure term requires the most input from the user, but is generally straightforward and controlled entirely by the user.

PROBABILITY OF EVENT

The P_e term is perhaps the most uncertain value. The value for this term is based upon accident history and expert opinion. A “Probability of Event” matrix has been created to provide this value based upon PES activity type and explosives type. Examples of PES activity type include: disposal, assembly, lab/test, loading/unloading, in-transit storage, and deep storage. Explosives types are based upon the compatibility groups defined in DoD 6055.09-M[2].

The probability of event term can also be modified by environmental factors. Environmental factors are intended to account for site-specific circumstances that could increase the potential for an explosives accident. Examples of environmental factors include operations outside the continental US, initial tests of new systems, operations involving exposed explosives, and operations occurring in hazardous environments with gases, fibers, etc.

This term requires the least amount of input from the user and relies heavily upon predetermined values not directly controlled by the user.

PROBABILITY OF FATALITY GIVEN AN EVENT

The $P_{f|e}$ term requires is the most complex portion of the process, but requires only a moderate amount of information from the user. The user specifies the type and amount of explosives, selects the PES and ES facility types, selects the roof type, and specifies the amount and type of glass at the ES facility.

With this basic input from the user, the probability of fatality given an event is calculated from a series of physics-based algorithms. These algorithms are defined in detail in DDESB Technical Paper 14[4].

TECHNICAL PAPER 14 PROCESS ARCHITECTURE

Figure 3 shows the 26-step process detailed in Technical Paper 14. A brief description of each step is provided below.

Input

- Input and Exposure Branch
    - Step 1 – Enter explosives data
    - Step 2 – Enter PES data and calculate the probability of event, P_e
    - Step 3 – Enter ES data and personnel exposure data, E_p
    - Step 4 – The explosives yield is calculated

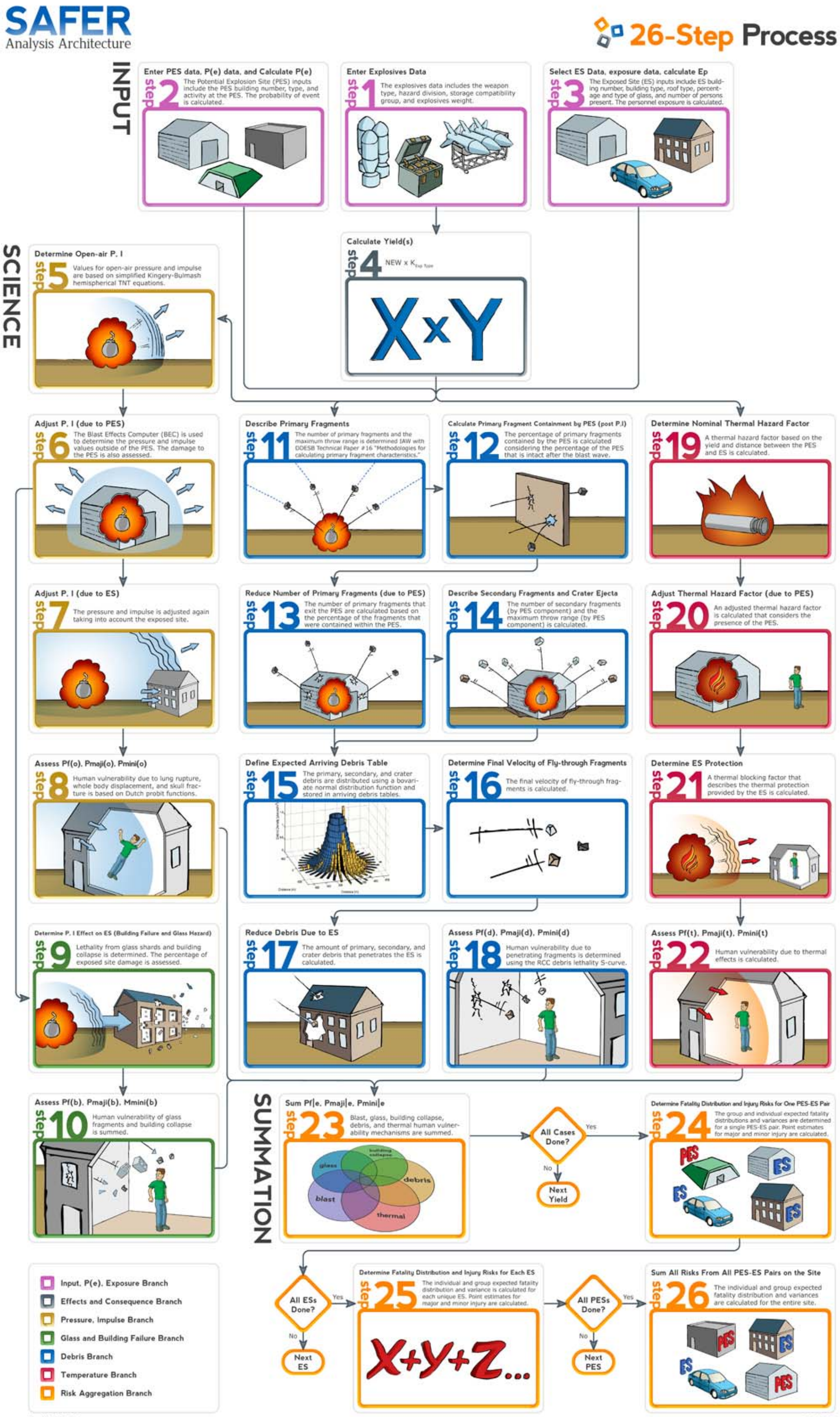

Figure 3 – Technical Paper 14 Process

Science

- Pressure and Impulse Branch
  - Step 5 – Determine the open-air pressure and impulse
  - Step 6 – Adjust the pressure and impulse due to the PES structure
  - Step 7 – Adjust the pressure and impulse due to the ES structure
  - Step 8 – Calculate $P_{f|e}$ due to overpressure
- Glass and Building Failure Branch
  - Step 9 – Determine level of building failure at the ES due to overpressure
  - Step 10 – Calculate $P_{f|e}$ due to glass and building failure
- Debris Branch
  - Step 11 – Determine the primary fragments (munition/test article debris)
  - Step 12 – Determine if primary fragments are contained by the PES
  - Step 13 – Reduce number of primary fragments due to the PES
  - Step 14 – Determine the secondary fragments (building/crater debris)
  - Step 15 – Determine quantity of fragments that reach the ES
  - Step 16 – Determine final velocity of fragments at ES
  - Step 17 – Determine quantity of fragments stopped by the ES structure
  - Step 18 – Calculate $P_{f|e}$ due to fragment debris
- Thermal Branch
  - Step 19 – Determine the open-air thermal hazard
  - Step 20 – Adjust the thermal hazard due to the PES structure
  - Step 21 – Adjust the thermal hazard due to the ES structure
  - Step 22 – Calculate $P_{f|e}$ due to the thermal hazard

Summation

- Risk Aggregation Branch
  - Step 23 – Sum the $P_{f|e}$ component terms to calculate the final $P_{f|e}$
  - Step 24 – Use E_p, $P_{f|e}$, and P_e to calculate E_f for one PES-ES pair
  - Step 25 – E_f is aggregated for all ES facilities affected by the PES
  - Step 26 – All risk is aggregated for all PES facilities on the site

The final product of the process is the Probability of Fatality (P_f) for a single person and the Expected Fatalities (E_f) for the entire site. These values are compared to acceptance criteria developed by the DDESB shown in Table 1.

Table 1 – DDESB Acceptance Criteria

Risk to:	**Criteria**
Any 1 person (Annual P_f)	Limit maximum risk to 1×10^{-6}
Any 1 related (Annual P_f)	Limit maximum risk to 1×10^{-4}
All public (Annual E_f)	Limit maximum risk to 1×10^{-5}
All related (Annual E_f)	Limit maximum risk to 1×10^{-3}

The Technical Paper 14 methodology includes a factor for uncertainty. This term artificially magnifies the risk to account for random variations and potential errors in input data. The user is asked what level of confidence they have in their input values. The details of the uncertainty factor are provided in Technical Paper 14.

BENEFITS OF A RISK-BASED APPROACH

Numerous benefits have been associated with a risk-based approach[5]. They include:

- Providing decision makers with the knowledge of the actual risk that is being accepted,

- A decrease in the number of waivers required,
- Prioritizing non-compliance (since a level of risk can be associated with each),
- Quantitative measures of risk can be compared to established criteria,
- Providing a means for identifying and prioritizing risk contributors as well as ways to mitigate these contributors, and
- Cost savings resulting from: better utilization of real estate, less expensive building designs, standardized waiver review and processing, and increased mission capability.

As a minimum, the benefits include consistency, a basis for decision making, reducing potential liability, and quantifying the risks that are taken.

In contrast, there are at least two factors which may reduce the benefits. More training may be needed because of the change to a new siting approach (compared to QD), and more extensive input is required from the user at the time of the analysis.

IMPLEMENTATION OF RISK-BASED SITING

In 1997, the DDESB chartered the Risk Based Explosives Safety Criteria Team (RBESCT) to define the feasibility and plan of action for adopting risk-based criteria for explosives safety within the DoD[5]. To date, the DDESB in conjunction with the service-specific safety centers have approved multiple risk-based site plans.

Under the direction of the RBESCT, a software program has been developed to implement the Technical Paper 14 process for risk-based siting. The software is called Safety Assessment for Explosives Risk (SAFER) and is developed by APT Research, Inc.

The development of criteria for risk-based siting has focused on the primary facility types used in the DoD for explosives storage and maintenance. These facility types include magazines, steel and concrete operations buildings, ships, and aircraft shelters. The munitions types have also been prioritized to represent the most common DoD applications.

Development of facility types that would represent energetic liquid test sites and storage areas is being discussed in the RBESCT. Currently, the RBESCT is seeking to develop improved criteria that phenomena such as coupling effects of overpressure, thermal, and fragment hazards. Creation of these criteria would allow a streamlined process to be used for submitting risk-based site plans for energetic liquid facilities.

Several other nations have adopted risk-based siting to various degrees. Switzerland introduced a quantitative risk analysis approach as early as the late 1960s. The United Kingdom, Norway, Australia, Germany, Singapore, and Sweden have also used risk-based methodologies. Many of these nations, together with the United States, participate regularly in the KLOTZ group to further the research of risk-based methodologies.

SUMMARY AND CONCLUSIONS

Significant effort has been made in creating risk-based analysis methods to more accurately quantify the hazards associated with explosives storage and handling. This method has the same ultimate goal of safety as the current QD method, but approaches the analysis in a significantly different manner. Risk-based siting has the potential to provide a better understanding of the hazards present at energetic liquid facilities. This in turn would allow better planning, potentially lower costs, and more flexibility in operations.

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